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PROGRESS REPORT
October 1, 1967 - September 30, 1968

MEASUREMENT AND DISPLAY OF CONTROL INFORMATION
(Remote Manipulation and Manual Control)

Thomas B. Sheridan
William R. Ferrell

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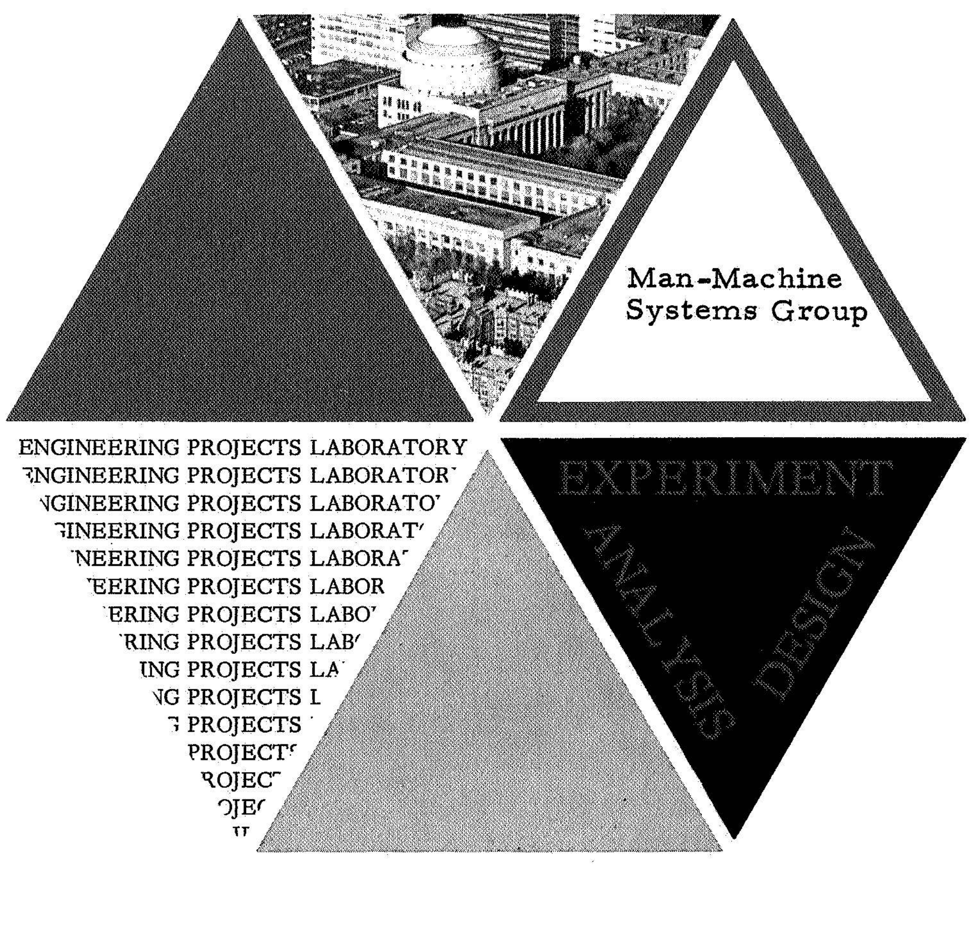

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INTRODUCTION

During the period October 1, 1967 to September 30, 1968 the Man-Machine Systems Laboratory engaged in a number of research projects under support of NsG 107-61.

A unifying theme for roughly half of the effort was remote manipulation - how man can extend his hands arbitrarily in space to accomplish useful work - exploration, maintenance, assembly - and this in spite of transmission delay, limited bandwidth and noise in the telemetry loop. Beginning with an experimental study of the effects of transmission delay, we have concluded that any good solution will involve utilizing man as an intermittent supervisory controller of a remote computer, which in turn controls the mechanical hand on a fast time scale with respect to inputs from its own sensors and a slower time scale based on commands from the human supervisor.

We are proceeding in five areas which we feel circumscribe the important control and instrumentation considerations: 1) formal task definition and performance criteria; 2) computer control and man-computer functional allocation; 3) command language development and display-control interface with human operator; 4) hardware design of manipulator and computer-manipulator interface; 5) sensors. (Progress is discussed herein according to these categories).

Other problems associated with implementing a human controlled remote computer-manipulator system, such as space power, telemetry, materials, lubrication, computer technology, and kinematics, are much better in hand than those of control.

We feel that relatively soon such systems will be seen as a more practical alternative than either sending an astronaut - with training and life support costs and hazard to human life - or than sending a fully instrumented and preprogrammed package into space with little if any flexibility for pattern recognition or change in subgoals or mode of activity. Potentially a closely supervised computer-manipulator can offer most of the flexibility of the astronaut without the attendant hazards and costs.

The other half of our effort for the reporting period has dealt with a variety of control problems of both discrete and continuous sorts. An investigation of the human operator as a time-optimal bang-bang state regulator of second order systems is being completed. Progress has been made on a theory of goal-directed maze solving and a model for human performance in such tasks. Work has been completed on a theoretical study interrelating two and three time scale preview control with optimal (Weiner-Hopf) control, Further work has been done on experiments and information transmission models of humans engaged in preview control tasks.

A. REMOTE MANIPULATION

A.1. An Experimental Study of Supervisory Controlled Remote Manipulation. - D. J. Barber

An experimental program has been started to investigate the performance of human controlled manipulator systems. The program is an extension of the work of W. R. Ferrell to the supervisory control of more intelligent manipulators. An attempt is being made to relate the performance and strategies used in simple manually controlled systems to the performance of computer aided, semi-automatic manipulators by describing tasks and human performance from an informational or decision theory viewpoint. We describe human control of manual systems in terms of the operators' uncertainty in the state of the manipulator and/or task environment.

Experiment 1: A program was written to simulate a two-dimensional manually controlled manipulator on a computer generated display scope. The program has facilities for varying the dynamics of the manipulator and the time delay between operator and manipulator - see Fig. 1. At a given delay T and dynamic lag τ, the operator is presented with a random series of step inputs or targets. He is told to move the system output to the target position in minimum time, and the time histories of his commands are recorded. These traces are then examined for evidence of either a continuous control strategy, or use of the "move and wait" strategy identified by Ferrell. Ferrell found this strategy was used consistently at delays down to 0.3 seconds when operating a position controlled (no dynamics) system.

A hoped for first result is a map of continuous regions and "move and wait" regions as a function of the delay and the lag. Preliminary results indicate that this is not a binary decision (which strategy to use) but that at some combinations of delay and lag a mixed strategy is used, where the operator makes long continuous moves with a few waits for correct feedback. The desired map will therefore be a surface indicating per cent time waiting as a function of delay and lag.

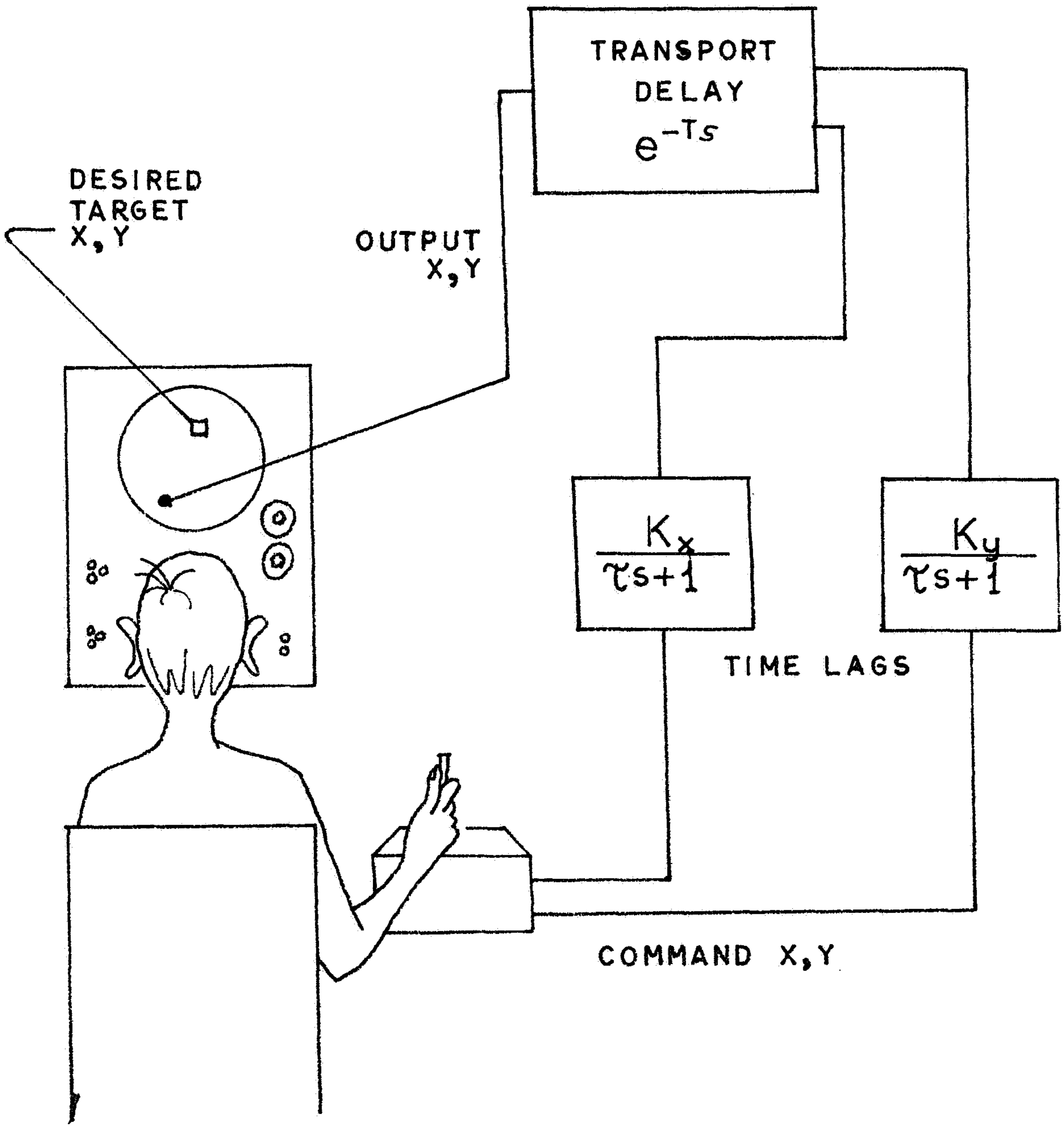

TRANSPORT
DELAY
e^{-Ts}
DESIRED
TARGET
X, Y
OUTPUT
X, Y
$\frac{K_x}{\tau s+1}$
$\frac{K_y}{\tau s+1}$
TIME LAGS
COMMAND X, Y

Fig. 1

A hypothesis suggested by J. Senders, is that the operator moves continuously until his uncertainty in the output position exceeds a tolerance, then waits (no control actions) until the delayed feedback is correct. Analytic efforts are now being made to describe the operator's uncertainty in terms of his previous control and the system parameters. This hypothesis, if validated, would not only describe when an operator uses a move and wait strategy, but also, given that he does, it should describe how long an open loop move he makes before waiting for feedback.

Preliminary results for Experiment 1 also indicate that the operator does not always wait until the system output has settled, or reached a steady state. For no error in the feedback, the operator would have to wait for a delay period plus approximately three lag time constants. Since some subjects begin moving before this time, it indicates that they are using velocity or some other derivative information to reduce their uncertainty enough to make another open loop move. A literature survey was undertaken to look for data on an operator's ability to estimate and extrapolate velocity information. It may be possible to extend this data to the case where the velocity is constantly changing and the operator has some knowledge, i.e., an estimate of τ, of the form of this variation. A simple experiment to check this extension has been tentatively designed.

Experiment 2: An operator is shown the output response of a lag to one of ten step input magnitudes. He estimates and marks his guess of the step steady state. From a record of the error of his guess, his transmitted information can be calculated. If this error information is a function of the time to mark, this relationship could then be applied to the time histories of Experiment 1. This would result in a time history of the operators' uncertainty, and the hypothesis of an uncertainty tolerance could be checked by seeing if indeed the uncertainty reached a maximum just before a wait for feedback.

Efforts are now being made to describe a realistic supervisory, or automatic manipulator system in terms of operator information. In particular, MANTRAN (see last progress report) is a finite vocabulary language for commanding a manipulator. The informational content of a MANTRAN statement can be calculated based on the allowed words in the vocabulary and their probability or frequency of use. If we then apply the relations from Experiment 2 to calculate the uncertainty in the operators feedback, it can be seen whether his command statements indicate he is reducing his total uncertainty to a tolerance.

A.2. State Space Models of Remote Manipulation Tasks - D.E. Whitney

I wrote and prepared my Ph.D. thesis entitles "State Space Models of Remote Manipulation Tasks".

I also prepared a technical paper on my thesis work, having the same title, and submitted it for publication in the IEEE Transactions on Automatic Control. Its abstract follows:

This paper presents a state variable formulation of the remote manipulation problem, applicable to computer-aided manipulation under human supervision or to autonomous robots. The state vector, which in previous formulations of this problem contained only variables describing the manipulative device itself, is expanded here to include vital parameters of the task site, including locations of objects and obstacles. This vector, suitably quantized, spans a discrete state space which contains many different static configurations of the manipulator and the objects to be manipulated. A manipulation task is specified as a new state which the operator wishes the manipulator-objects-obstacles system to occupy. Admissible controls include quantized basic motions of the manipulator's jaws, plus grasp, release, push, twist and so on. Costs of executing these controls or of arriving at a given state are assigned by the operator to reflect his priorities concerning time, fuel, risk, uncertainty, or some normalized combination of these. A method similar to Dynamic Programming finds a shortest path from the present to the desired state. This path represents the optimal control history to be followed.

This method is automatically capable of such necessary manipulative skills as obstacle avoidance, rendezvous of jaws with object to be grasped, proper timing of grasp and release, incorporation of new information concerning object and obstacle locations, plus keeping track of the changes

which the manipulator makes as it moves things around. Methods of relieving dimensionality problems are discussed, including allowing the operator or a heuristic to suggest subgoals, from which a higher level optimization scheme may select the optimal ordering. Several examples are given.

A.3. Supervisory Control System for Remote Manipulation Using Hierarchical Aspects of Manipulation Tasks - P. Hardin

This is the continuation of the project which began as "Manipulator Control Through Natural Language". In developing the algorithm for the sentence parser, experiments were performed which indicated that a simplified technique of decoding input commands could be used. It was determined that the operator chose to use only imperative sentence forms to control a simulated manipulator. Hence, it was inferred that an operator would use only imperative forms to control a real manipulator.

With this information, a simpler comparison routine can be used instead of the sentence parsing routine. The comparison routine masks words in the input string to check them against words the computer recognizes. As the computer recognizes words in the input string, it arranges them into an internally useful form.

This internal form is a function which requests changes in the manipulator's position or changes in the manipulator's environment. Typically, such a function will specify the goal state or arrangement of the environment the manipulator is to achieve. The function can also imply the method the manipulator is to use to change the environment.

The program for planning the manipulator motion is to take advantage of the hierarchical structure of manipulation tasks. Whitney, in his thesis, alluded to the possibility of a hierarchical structure of manipulation tasks in using "atoms" of manipulation motion. Strings of these "atoms" describe all possible manipulator motions, and, hence, all possible tasks the manipulator can perform. (The "atoms" represent incremental manipulator jaw motions.) Whitney demonstrated a method of combining atoms into requested manipulator motions. The motion requests had to be kept fairly simple, however, as Whitney used a state space representation of the system.

The hierarchical aspects of manipulation tasks become useful when one considers simple tasks like "Move block N to position A" as atoms for more complicated tasks. For instance, building a row of blocks is just a sequence of the above MOVE commands. Similarly, the construction of a rectangle with blocks is a sequence of building rows. This hierarchical structure can be used to advantage to design a manipulation scheme which can plan and direct the execution of a quite complex appearing task.

Algorthms have been written which use the above techniques to move square blocks on a plane surface. The system, is capable of extensive rearrangement of the space with very little input from the human operator. A demonstration of the above system should be completed shortly.

A.4. Manipulator Control through Open Mechanisms - D. E. Whitney[+]

Currently I am investigating the mathematics of open mechanisms (of which manipulators and human prostheses are examples) for the purpose of designing control schemes which utilize a state-space point of view. It appeared from the literature that the usual rate control schemes require the operator to activate the prime movers of the mechanism one at a time, often with little or no speed variability. The result is that the operator may not know what switches to throw (or the order in which to throw them) in order to achieve his desired trajectory (to avoid obstacles) or to rendezvous with some object. For this and other reasons, rate control is slow.

My goal was to design control schemes in which the operator directly could request trajectories or goal points; the controller would turn on the motors at the right times and set their speeds so that the trajectory would be followed. The solutions I derived stem from manipulation of the basic equation for the mechanism, taken as a geometric device only, with no dynamics:

$$x = f(\theta) \qquad (1)$$

[+]Supported in part by the U.S. Public Health Service Vocational Rehabilitation. Administration.

Here, θ is a vector of joint angles, which can be related by various linear methods to the positions of the various prime movers. x is a vector which contains the position and (possibly) orientation of the mechanism's endpoint. Since our desire is to control the endpoint position and orientation history in time, Eq. (1) is actually backwards. What we need is its inverse,

$$\theta = g(x) \tag{2}$$

That is, we supply the x we want and Eq. (2) will tell us what θ to use, hence what prime mover positions to drive toward. Unfortunately, Eq. (2) is usually impossible to obtain. The aim of the work was therefore to get something like Eq. (2) in spite of the difficulty.

For rate control, we may do the following: Differentiating Eq. (1) with respect to time, we have

$$x = J(\theta)\,\theta \tag{3}$$

where $J(\theta)$ is the Jacobian matrix of $f(\theta)$. If the dimension of θ equals that of x, $J(\theta)$ is square so that where ever $J^{-1}(\theta)$ exists, we may write

$$\theta = J^{-1}(\theta)\,x \tag{4}$$

Providing we have θ feedback available for calculating $J(\theta)$, Eq. (4) allows us to specify the direction in which we want the endpoints to move, and Eq. (4) will tell us what direction to move each prime mover.

Various approximations to this kind of control are also derived and discussed in a technical paper which I prepared and submitted for publication in the IEEE Transactions on Man-Machine Systems under the title "Methods of Rate and Position Control of Remote Manipulators and Human Prostheses". Its abstract follows:

The Mathematics of remote manipulators and human prostheses is analyzed for the purpose of deriving rate and position control schemes which result in resolved motion. That is, the operator is enabled to call for the desired manipulator endpoint motion directly, and is not limited to pushing switches which are tied one-to-one (by whatever design of control box or joystick) to the manipulator's prime movers. A number of schemes is proposed, some analog, some digital, some requiring joint angle feedback from the controlled device, some not requiring it. Some methods are tailored to human operators (such as control axes aligned to the jaw or prosthetic hand axes), and some are suited to digital computers (for human supervisory control). Several schemes are simple enough that one may envision them realized for human prosthetics with existing electronic technology.

A.5. Heuristic Path Generation Algorithms - B. M. Harder

Consider the problem of constructing the shortest path through a field of three-dimensional obstacles. A heuristic has been designed to arrive at a solution which approaches the optimal manipulator motion time and path calculation time.

The heuristic is based on an iterative technique for selecting a candidate path. The algorithm first calculates the path swept by the jaw during straight-line motion from start to goal. Then this line is tested for intersection with the planes circumscribing each obstacle in the obstacle list. If intersections are calculated, an intermediate subgoal will be selected according to a limited set of heuristics. One of these heuristics will be selected by an estimate of the time involved in using it to pass the first obstacle. An example in the selection of a heuristic occurs when the first obstacle is a large wall with a hole in it. If the hole is too small to pass the manipulator jaw and contents, yet large enough to pass them one at a time, the choice is between going around the wall with contents in jaw or inserting the contents through the hole and then following it with the jaw. The most effective solution is chosen as a subgoal and the algorithm solves the problem of moving first to subgoal, then to goal. This recursive process of selecting another subgoal may be required several times during the process of threading through a large number of obstacles. When the first complete candidate path is found, the time to move through the path is computed. This time is compared with an independent estimate of the optimum path motion time. This is a measure of estimated inefficiencies due to selecting a poor subgoal in an intermediate step.

After the first candidate path has been found, other candidate paths may be evaluated by selecting other plausible subgoals and computing the time for motion. Whenever other candidate paths are found to have a lower motion time than the previous best path, the new best path replaces the previous path. This process of optimization continues until the heuristic search truncation test (HSTT) is satisfied. The HSTT compares the maximum expected improvement in motion time to the calculation time spent on this optimization. When the calculation time exceeds the expected gains in motion time, the best path at that time is selected for motion.

A.6. Manipulation System Design - B. M. Harder

A comprehensive design of a supervisory controlled manipulator system has been begun. The requirements for systems to be used in various space applications must be determined. Numerous manipulator systems in existence are being investigated. The relationship of the arm kinematics to the ease of computer control is a major factor.

A.7. Touch Sensor Analysis and Design - S. Leighton

The purpose of this effort, by contrast to earlier work on an optical (visual display) touch sensor, is to design a workable display of manipulator touch patterns directly to the human operators skin.

a. For the purposes of dynamic analysis I have investigated three existing digital computer programs for simulating analog mechanical systems. These are: Dynamo, Digital Simulation Language (DSL), and Continuous Systems Modeling Program (CSMP). CSMP was found to be the best from the standpoint of availability and ease of problem statement. I am currently running a CSMP program to simulate the display end of a touch sensor/display system.

b. A very crude and simple experiment with an air jet seems to indicate that that medium, air jets, would have adequate resolution for a touch display. I need to do much more in this area, and feel that I can learn a great deal from similar simple experiments, leading eventually to some sort of matrix display.

c. I am trying to determine the feasibility of the "fluid-conductivity" sensor with other very simple experiments. These consist of measuring the resistance between two electrodes immersed in water and water-salt solutions. The idea is to see what problems of gas production and distance insensitivity exist.

MANUAL CONTROL

B.1. Human Performance in a Bang-Bang State Regulation Task with Phase Plane Displays - D.C. Miller

The ability of a well-trained human controller to perform a time-optimal state regulation task with each of two second order systems has been studied. Three subjects were thoroughly trained in the control of a double integrator system and an undamped oscillator system. In each case, they were required to bring the state of the controlled system from a series of arbitrary initial conditions to the origin of the phase plane in minimum time.

The proper performance of this task requires the execution of a well-defined discrete response strategy. This strategy requires the control to be switched between its positive and negative limits as a function of the state of the system. Therefore, the subjects were provided with a toggle switch with which to control the input.

Switching error data were collected for at least 300 trials from each subject using several different displays. These included a switch curve display (in which the optimum strategy is explicitly shown), a predictor display (in which the alternative future state trajectories are shown emanating from the present state), a phase plane display (in which no strategy aids are used), and a single variable display (a one-dimensional display, in which only the lowest order state variable is shown). These displays provide the subjects with varying amounts of information. Therefore, a comparison between the subjects' performances with the various displays provides a means for identifying the errors which arise during the execution of each of the task components.

Models were developed by identifying the task components and by applying knowledge of the psychophysical characteristics of the human controller. The models so developed were checked for consistency by combining them in various ways to model the subjects' performance with each display.

The results of this investigation will soon be submitted as a doctoral thesis, which will also be released as a formal research report. This report will include discussions of several aspects of the results. These include: 1) the optimality of the human controller in discrete response tasks; 2) the design and evaluation of displays for use in such tasks; and 3) techniques for modeling human performance in such tasks by a synthesis of subtask models which are simple enough to treat in terms of the known psychophysical characteristics of the human controller.

B.2. A Limited-Preview Goal-Directed Maze Solver - W. H. Vickers

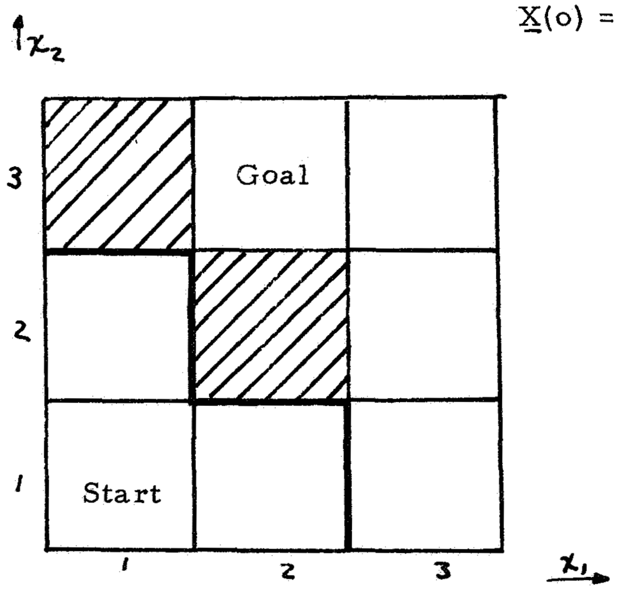
There are two main questions with implications for computer controlled manipulation that this project hopes to answer. First we want to find the trade-off between performance and the preview of the environment. The underlying assumption here is that we do not have to find an optimal path in order to find a satisfying one (satisfies given criteria). Secondly, given that we decide to use a limited preview approach, what is the trade-off between performance and complexity (or computation time) of the heuristic program for solving it. In keeping with this second objective recent work has been directed toward understanding how the best possible limited-preview strategy should operate.

We should first define what is meant by the best strategy for a given preview. This is the strategy s^+ which chooses each move to minimize the expected path length using strategy s^+ $L_s{}^+$) for the rest of the way. In other words assuming that we will act optimally after the present move, we will choose the present move on the basis of least expected path length for the remainder of the path to the goal. This is an optimal strategy but note that it does not claim to find the optimal path. However, it will have a smaller expected path length than any other strategy which uses only the same information.

It should be mentioned here that if we have a strategy s_1 we can show that the strategy s_2 which chooses moves on the basis of smallest expected path length using strategy $s_1 L_{s1}$ is a better strategy. This conceivably could give us a way to make one step improvements on our strategies, although calculating L_s is not easy.

There is a way to calculate the optimal strategy using dynamic programming. The essence of the idea is to define an expanded state vector to take account of the state of knowledge as well as the physical location. This makes the strategy a function only of the current state and independent of past history; i.e., a Markov process. The problem with this procedure is that memory requirements grow so rapidly that only small problems are computationally feasible. For an N x N physical space it requires an $N^2 + 2$ dimensional state vector with $(3^{N^2} \cdot N^2)$ points in the state space. For any interesting problem therefore it becomes unmanageable. It is however a good instrument for gaining insight into the problem.

Consider a two-dimensional physical space where some locations may contain obstacles preventing entry. The maze solver can see only one unit in all directions. The expanded state vector is a $(N^2 + 2)$ dimension vector $\underline{X}$. For example for the physical space of Fig. 1, the state vector at the start (assuming that the goal is clear) would be:



$$\underline{X}(o) = \begin{bmatrix}1\\1\\0\\0\\P\\0\\P\\0\\P\\P\\P\end{bmatrix} = \begin{bmatrix}x_1\\x_2\\a_{11}\\a_{12}\\a_{13}\\a_{21}\\a_{22}\\a_{23}\\a_{31}\\a_{32}\\a_{33}\end{bmatrix}$$

position in physical space

a_{ij} = state of knowledge about obstacle at position (i, j)

$= \begin{cases} 0 \text{ if it is known to be empty} \\ 1 \text{ if it is known to be blocked} \\ P \text{ if it is unknown} \end{cases}$

Let us look at the rest of the system description. To use dynamic programming we need a state transition equation and a cost criterion.

The transition equations, ($\underline{X}_{k+1} = f(\underline{X}_k, \underline{u}_k, \underline{\tilde{\omega}})$ are:

$$x_i(k+1) = x_i(k) + u_i(k) \qquad i = 1, 2$$

$$a_{ij}(k+1) = \begin{cases} w_{ij} \text{ if } \left\| \begin{pmatrix} X_1(k+1) \\ X_2(k+1) \end{pmatrix} - \begin{pmatrix} i \\ j \end{pmatrix} \right\| \leq \text{Preview} \\ a_{ij}(k) \text{otherwise} \end{cases}$$

where u(k) is the control exerted at period k

$$\underline{u} \in \left\{ \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \begin{pmatrix} -1 \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \begin{pmatrix} 0 \\ -1 \end{pmatrix} \right\}$$

and $\underline{\tilde{\omega}}$ is a random vector that represents the true but unknown status of obstacles, i.e.,

$$\underline{\omega}^T = (0 \ \ 0 \ \ 1 \ \ 0 \ \ 1 \ \ 0 \ \ 0 \ \ 0 \ \ 0) \text{ for this case.}$$

We must use a random forcing vector in the state equations since the transitions are not determined solely by the control $\underline{u}$, but also by what we see when we get to the new location.

This equation says that we can move only one step at a time along the coordinate axes, and that the information about a location cannot change unless we can see it.

The cost criterion is total path length, i.e.

$$J = \sum_{k=0}^{N} g(\underline{X}(k), \underline{u}(k), \underline{\omega})$$

where g is the cost of being in state X, using control u, and having $\underline{\tilde{\omega}} = \omega$, i.e.,

$$g = \begin{cases} \infty \text{ if we try to go through a blocked state} \\ 1 \text{ otherwise} \end{cases}$$

and N is the total number of steps needed to meet the condition $\underline{X}(N) \in$ Goal set.

The dynamic programming approach employs the fact that the expected cost using optimal strategy is a function only of the state. So we define a function $h(\underline{X}) = \min\limits_{\underline{u}} \operatorname*{Exp}\limits_{\underline{\omega}} (J)$

This can be identified as the expected path length under optimal strategy. We can also write a recurrence relation for $h(\underline{X})$ in the standard way,

$$h(\underline{X}_k) = \min_{\underline{u}_k} \quad \operatorname*{Exp}_{\underline{\omega}} \left\{ g(\underline{X}_k, \underline{u}_k, \underline{\omega}) + h\left[f(\underline{X}_k, \underline{u}_k, \underline{\omega}) \right] \right\}$$

with boundary condition $h(\underline{X}_g) = 0$ for $\underline{X}_g \in$ Goal set.

Now let us consider an algorithm that gives near optimal strategy without using an expanded state vector, and thus is much less expensive to use.

Consider a two-dimensional physical space as before, and let $\underline{X}$ be the physical space coordinate vector (X, Y). In order to start the algorithm an initial guess of the expected cost of reaching the goal from every state $\underline{X}$ is made. Call this $I^0(\underline{X})$. We improve our estimate of $I(\underline{X})$ as follows:

$$I^{(j+1)}(\underline{X}) = \operatorname*{Exp}_{\tilde{U}(\underline{X}) \in \mathcal{U}} \left\{ \min_{\underline{u} \in \tilde{U}(\underline{X})} \left[g(\underline{X}, \underline{u}) + I^{(j)}(f(\underline{X}, \underline{u})) \right] \right\}$$

where

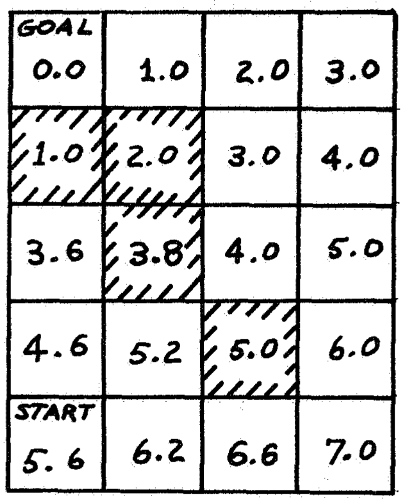
$\tilde{U}(\underline{X})$ is the set of legal controls that can be applied at a state $\underline{X}$. This is a random set since a priori we do not in general know which controls are allowed.

$\mathcal{U}$ is the set of all sets of controls, i.e.

$$\left\{ \cdot\,, \uparrow, \rightarrow, \downarrow, \leftarrow, \Lsh, \updownarrow, \ldots, \text{✣} \right\}$$

When we have finished several iterations and $I(\underline{X})$ has converged then we choose the control that minimizes $I(f(\underline{X}, \underline{u}))$. Whenever we actually see a new state (whose status had been uncertain) we must recalculate $I(\underline{X})$, based on this new information. Note that when the preview includes the whole maze, this procedure takes the optimal path.

This algorithm has been implemented on the computer and tried on some very simple mazes. For example on the maze of Fig. 2, this procedure converged to the numbers given. These numbers do not represent expected path length under optimal strategy but they do give an approximation to the relative value of the various states taking account of everything that is known about the maze.



Probability that a shaded state is blocked = 1/2.

Numbers refer to I(X)

Fig. 2

In addition to the theoretical work just mentioned, most of the computer programs needed to input mazes and output results from any maze-solving procedure have been completed. Very shortly we will be in a position to compare various heuristic maze-solvers on a class of random mazes for various preview constraints. We also expect to see how well these programs compare with human maze solving.

B.3. Preview Control: Techniques Employing One and Two Fast Time Models and their Relation to Modern Control Theory - R. A. Miller

The preview control problem (input values known a constant time into future, i.e., a constant time prior to requiring conformance of plant to these same input values) has been formulated in terms of modern control theory. The two-time-scale (or fast-time-model) technique is shown to suggest interesting simplicities at the sacrifice of some approximation to the optimal solution. It therefore retains some promise as a model for human preview control. However to make the two-or multi-time-scale system exact requires solving a Riccatti equation and therefore offer no advantages over conventional control techniques if the true optimal is desired.

A report on this work is being published.

B.4. The Effect of Preview on Information Processing - W.R. Ferrell

Investigation has proceeded in two directions following the discovery that information transmission rate for typing when preview is restricted is determined by the information content of the preview rather than its physical extent or the number of items in it. Attempts have been made to see whether the finding also applies to other sensory motor tasks and attempts have been made to construct a mathematical model of the phenomenon.

During the past year it has been found that pencil tracing through patterns of randomly scattered obstacles with restricted preview also results in a single curve of information "passing" or processing rate versus information in the preview for different obstacle densities. However, to account for the data for low information density and large preview it is necessary to assume that there is a physiological limitation on the preview distance that can be attended to.

Several models which give curves that fit the typing data have been tested. The most promising predicts the letter rate versus letters in the preview curve for the random letter case. It assumes a single channel decision maker in tandem with a single channel output device. Both can operate independently except that the lengths of queues in front of them are constrained by the preview. As the preview gets longer, there are fewer times when one must wait for the other. It is hoped that this model will also be capable of predicting the performance on typing of text.

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